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TRANSFER OF LONG WAVE RADIATION IN THE LOWER ATMOSPHERE OF VENUS

M. Ya. Marov and V. P. Shari

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16. Abstract

Radiative heat flows in the subcloud atmosphere based on the latest data on the Venusian atmosphere were calculated, using new results on the absorption of the main atmospheric constituent -- carbon dioxide gas. Assuming a value of A = 0.77 ± 0.01 for the integral albedo of Venus, the exiting thermal radiation flux at all altitudes considerably exceeds the mean inflow of solar energy. Even for a relative H_2O content of 10^{-5}, the balance cannot be achieved. But the exiting thermal radiation flux can be reconciled with the incoming solar flux for the same or smaller albedo if the relative H_2O content in the atmosphere is ∿0.1%. The most substantial contribution to radiation transfer is made by the 4050-4650 cm^{-1} "window" between the 2.7 and 2.0 μm CO_2 bands: the upper half of the subcloud atmosphere accounts for more than 60% total thermal flux.

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TRANSFER OF LONG WAVE RADIATION IN THE LOWER ATMOSPHERE OF VENUS

M. Ya. Marov and V. P. Shari

As a result of experiments conducted on the Venera 4,5,6,7, and 8 Interplanetary Automatic Stations, the principal chemical composition and altitude profiles of temperature and pressure in the atmosphere of Venus were measured down to its surface on the nightside and dayside of the planet [1, 2]. The results show that detectable diurnal variations on Venus near the morning terminator are absent. Temperatures and pressures at the surface are as follows: $T = 747 \pm 20°C$; $P = 90 \pm 15$ kg/cm^2 (Venera 7) and $T = 741 \pm 7°K$, $P = 93 \pm 1.5$ kg/cm^2 (Venera 8). From the results of direct measurements, a model of the Venusian atmosphere was calculated which corresponds to the altitude profiles of T and P used in the calculations. They are shown in Fig. 1 up to an altitude of 60 km where the lower boundary of H_2O clouds should be, approximately, for a ratio of the mixture corresponding to the results of measurements on the Venera interplanetary automatic stations. /3*

The aim of this study is to calculate the distribution of radiative heat flows in the subcloud atmosphere based on the latest data on the physical structure of the atmosphere, using the new results on the absorbing characteristics of the main constituent of the atmosphere -- carbon dioxide gas [3, 4, 5].

For the most part, these are the results of theoretical calculations based on investigating the fine structure of the CO_2 absorption bands in the infrared spectral region at high pressures and temperatures to 800°C.

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* Numbers in margin indicate pagination in the foreign text.

They included the following:

1. Calculation with reference to the Fermi-resonance of spectroscopic constants for 900 vibrational states of $C^{12}O_2^{12}$, required to find the positions and intensities of the lines at high temperatures. /4

2. Calculation of the positions and intensities of the lines for 400 vibrational transitions lying in the range 1-20 m and forming the following bands: 1.2, 1.4, 1.6, 2.0, 2.7, 4.3, 4.8-5.2, 9.4-10.4, and 1.5 m. The intensities were calculated for temperatures from 295°K to 800°K, with a 50°K temperature step.

3. Selection of the method and calculation of parameters required to determine the CO_2 transmission functions for $P \geq$ 2-5 atm and $295° \leq T \leq 800°K$.

As shown in the work [4], in these conditions a fairly good agreement with experimental data is provided by calculating the transmission function in the weak line approximation based on the following expression:

where s is the mean line intensity in the interval $\Delta\omega$;

d is the mean spacing between lines;

s/d $(atm^{-1} \cdot cm^{-1})_{STP}$ are reduced to STP conditions; and

u is the content of the absorbing compound at STP;

$$u = \frac{273}{T} p\ell \ (atm \cdot cm)_{STP};$$

In this approximation, the values of $\bar{s}/d$ can be regarded as mean absorption coefficients in the interval $\Delta\omega$.

Based on this method, $\bar{s}/d$ values were obtained for the intervals $\Delta\omega = 10\ cm^{-1}$ in the infrared spectral region of CO_2 from 130 to 8310 cm^{-1} in the temperature range 295-800°K, with a 50°K step.

Spectral regions beyond the quanta of the 2.7 and 4.3 μm bands play a major role in the transfer of intrinsic radiation given the physical conditions of the subcloud atmosphere of Venus. Here the absorption is determined by the effect of the wings of the intense lines situated in the center of the band (absorption /5
coefficient $\tilde{K}$) and by the weak lines of hot transitions [3]. The absoption coefficients beyond the quantum of the 4.3 μm band were obtained by direct calculation, using the Benedictus contour. Data on transmission beyond the quantum of the band obtained experimentally by the Birch group [3] was used for the 2.7 μm band. Beyond the band quanta, the transmission function was determined by the following formula:

$$\tau_{\Delta\omega} = \exp\left\{-\frac{\bar{s}}{d} u + \tilde{K} p u\right\}$$

The dependence of the absorption coefficient K on the temperature was assumed to be as follows:

$$\frac{\tilde{K}(T)}{\tilde{K}(295^\circ)} = \frac{295}{T} \frac{(\bar{s}/d)_{max}(T)}{(\bar{s}/d)_{max}(295)}$$

where: "max" indicates the value in quanta.

In the calculations, experimental data on the induced absorption of CO_2 in the 7.2 and 7.8 μm bands combined in the 7.5 μm band were also taken into account. With reference to the induced absorption, the transmission for 10 cm^{-1} spectral intervals was calculated by the following formula:

$$\tau_{\Delta\omega} = \exp\left\{-\left[\frac{S}{d}\cdot u + K_{\Delta\omega}(294)\left(\frac{294}{T}\right)^5 \cdot p^2 \cdot \ell\right]\right\}$$

where: $K_{\Delta\omega}(294)$ is the induced absorption coefficient at 294°K.

Fig. 2 shows the distribution of the absorption coefficients of CO_2 based on the wave numbers for 10 cm^{-1} intervals given the conditions of the subcloud atmosphere of Venus at the surface and at the cloud level.

In the calculations of thermal fluxes for models of an atmosphere containing H_2O, data from the paper [6] on the absorption coefficients for the temperatures 300, 600 and 1000°K in the infrared spectral region, averaged by 25 cm^{-1} intervals, were used as the H_2O absorption coefficients. The transmission functions in these intervals were also determined in the weak line approximation. Fig. 3 presents a comparison of the H_2O absorption coefficients and the CO_2 absorption coefficients averaged over 25 cm^{-1} intervals (based on the data for 10 cm^{-1}) for conditions at the planetary surface, along with three values of relative H_2O content: 1%, 0.1%, and 0.001% (CO_2 -- 100%). /6

A scheme for calculating the diffuse radiative thermal fluxes in the subcloud Venusian atmosphere was selected in accordance with available data on absorption characteristics.

Scattering was not taken into account. And this layer of the atmosphere was assumed to be plane-stratified.

In these conditions, the equations for the spectral radiation intensity I^+ in the upper hemisphere (the values of the zenith angles $0 \leq \theta \leq \pi/2$) and I_ω^- intensities in the lower hemisphere ($\pi/2 \leq \theta \leq \pi$) can be represented in a form that is convenient from the standpoint of assigning boundary conditions:

$$\xi \frac{dI_\omega^\pm(z,\xi)}{dz \cdot K_\omega} = \pm\left(I_{p\omega}(z) - I_\omega^\pm(z,\xi)\right), \tag{1}$$

where: $\xi = \cos\vartheta \quad (0 \le \vartheta \le \pi/2)$

$I_{p\omega}$ is the spectral intensity of equilibrium radiation.

The presence of one diffusely reflecting surface at $Z = Z_0^+$ with blackbody factor ε, which in the following treatment will be assumed to be frequency-independent, will be a form of boundary conditions, sufficiently general for these equations, and modeling actual conditions at the planetary surface Z_0^+ and at the lower cloud level Z_0^-.

$$I_\omega^\pm(z_0^\pm,\xi) = \varepsilon^\pm I_{p\omega}(z_0^\pm) + (1-\varepsilon^\pm)\frac{2\pi\int\limits_0^{\pi/2} I_\omega^\mp(z_0^\pm,\xi)\cos\vartheta\sin\vartheta\, d\vartheta}{2\pi\int\limits_0^{\pi/2}\cos\vartheta\sin\vartheta\, d\vartheta} \tag{2}$$

For the case when the value $\varepsilon = 1$ is assigned to one surface of the plane layer, and an arbitrary value of ε to the other, the system of equations (1) with boundary conditions (2) becomes closed. /7

The solution to this system written in quadratures is expressed thusly:

$$I_\omega^\pm(z,\xi) = I_\omega^\pm(z_0^\pm,\xi)\, e^{-\int\limits_{z_0^\pm}^{z}\left[\pm\frac{K_\omega}{\xi}(z'')\right]dz''} + \int\limits_{z_0^\pm}^{z}\left[\pm\frac{K_\omega(z')}{\xi}\right] I_{p\omega}\, e^{-\int\limits_{z'}^{z}\left[\pm\frac{K_\omega}{\xi}(z'')\right]dz''} dz'$$

After transformation, we get

$$I_\omega^\pm(z,\xi) = \left[I_\omega^\pm(z_0^\pm,\xi) - I_{p\omega}(z_0^\pm)\right] e^{-\left|\int\limits_{z_0^\pm}^{z}\frac{K_\omega(z'')}{\xi}dz''\right|} - \int\limits_{z_0^\pm}^{z} e^{-\left|\int\limits_{z'}^{z}\frac{K_\omega(z'')}{\xi}dz''\right|} dI_{p\omega}(z') + I_{p\omega}(z)$$

Integrating the expressions for the spectral intensities over the frequency intervals $\delta\omega_i$ that are sufficiently small for changes in $I_\omega^\pm$ and $I_{p\omega}$ to be neglected within their limits, we get

$$I_i^\pm(z,\xi)=\left[I_i^\pm(z_0^\pm,\xi)-I_{pi}(z_0^\pm)\right]\cdot\bar{\tau}_i(z_0^\pm,z,\xi)+ \\ +I_{pi}(z)-\int_{z_0^\pm}^{z}\bar{\tau}_i(z',z,\xi)\,dI_{pi}(z') \tag{3}$$

The last expression includes the transmission functions as follows averaged over the frequency intervals $\delta\omega_i$:

$$\bar{\tau}_i(z_1,z_2,\xi)=\frac{\int_{\delta\omega_i} e^{-\left|\int_{z_1}^{z_2}\frac{k_\omega(z'')}{\xi}dz''\right|}d\omega}{\int_{\delta\omega_i} d\omega}$$

The subscript i relates the values to the i-th spectral interval.

The projection of the vector of the monochromatic flux of diffuse radiative energy on the altitude direction Z for the plane-stratified atmosphere is determined by the expression: /8

$$S_{\omega z}(z)=2\pi\int_0^\pi I_\omega(z,\vartheta)\cos\vartheta\cdot\sin\vartheta\cdot d\vartheta= \\ =2\pi\int_{-1}^{1}I_\omega(z,\xi)\,\xi\,d\xi$$

This integration was performed numerically by the Gaussian formula [7]. The Gaussian formula expresses the value of the integral approximately as follows

$$\int_{-1}^{1}g(x)dx\cong\sum_{r=1}^{n}w_r\,g(x_r)$$

where the nodes x_r and the weights corresponding to them w_r are independent of the choice of the integrand. The weights w_r are defined by the formula

$$w_r = \int_{-1}^{+1} \frac{\prod_n (x)}{\prod_n'(x_r)(x-x_r)}\, dx ,$$

where $\prod_n (x) = (x-x_1)\cdot(x-x_2)\cdot\ldots\cdot(x-x_n)$;

and $\prod_n'(x)$ denotes $\frac{d}{dx}(\prod_n (x))$; $\sum_{r=1}^{n} w_r = 2$;

If we take the roots of the equation $P_n(x) = 0$ as x_r, where $P_n(x)$ are Legendre polynominals, the corresponding formula for the Gaussian quadratures using n points will be exact for all polynominals whose order is less than 2n. Table presents the values of the nodes x_r and the weights w_r corresponding to them for the Gaussian formula. From the table it follows that there are k pairs of roots x_y -- for even values n = 2 k -- equal in magnitude and opposite in sign, and the weights w_r corresponding to each pair are equal to each other.

By computing the diffuse flux $s_{\omega z}$ by the Gaussian formula for n = 2k, we get: /10

$$S_{\omega z}(z) = 2\pi \int_{-1}^{1} I_\omega(z,\xi)\cdot\xi\, d\xi \cong 2\pi \sum_{r=1}^{n} w_r I_\omega(z,\xi_r)\cdot\xi_r =$$
$$= 2\pi \left\{ \sum_{r=1}^{k} w_r I_\omega(z,\xi_r)\xi_r + \sum_{r=1}^{k} w_r I_\omega(z,-\xi_r)(-\xi_r) \right\} =$$
$$= 2\pi \left\{ \sum_{r=1}^{k} w_r \xi_r I_\omega(z,\xi_r) - \sum_{r=1}^{k} w_r \xi_r I_\omega(z,-\xi_r) \right\}$$

The positive roots are subsumed under ξ_r. Since negative values of $\cos\theta = \xi$ correspond to the distribution of radiative energy in the lower hemisphere ($I = I^-$) and the positive values of cos $\cos\theta = \xi$ correspond to the distribution of radiative energy in the upper energy ($I = I^+$), we will have

TABLE 1. NODES AND COEFFICIENTS FOR THE GAUSSIAN FORMULA

	$n=1$	
$x_1 = 0$		$w_1 = 2$
	$n=2$, $k=1$	
$x_1 = -x_2 = 0.57735\ 02692$		$w_1 = w_2 = 1$
	$n=3$	
$x_1 = -x_3 = 0.77459\ 66692$		$w_1 = w_3 = \frac{5}{9}$
$x_2 = 0$		$w_2 = \frac{8}{9}$
ξ_r	$n=4$, $k=2$	w_r
$x_1 = -x_4 = 0.86113\ 63116$		$w_1 = w_4 = 0.34785\ 48451$
$x_2 = -x_3 = 0.33998\ 10436$		$w_2 = w_3 = 0{,}65214\ 51549$
	$n=5$	
$x_1 = -x_5 = 0.90617\ 98459$		$w_1 = w_5 = 0.23692\ 68851$
$x_2 = -x_4 = 0.53846\ 93101$		$w_2 = w_4 = 0{,}47862\ 86705$
$x_3 = 0$		$w_3 = 0.56888\ 88889$
ξ_r	$n=6$, $k=3$	w_r
$x_1 = -x_6 = 0{,}93246\ 95142$		$w_1 = w_6 = 0.17132\ 44924$
$x_2 = -x_5 = 0.66120\ 93865$		$w_2 = w_5 = 0{,}36076\ 15730$
$x_3 = -x_4 = 0.23861\ 91861$		$w_3 = w_4 = 0{,}46791\ 39346$
	$n=7$	
$x_1 = -x_7 = 0.94910\ 79123$		$w_1 = w_7 = 0.12948\ 49662$
$x_2 = -x_6 = 0.74153\ 11856$		$w_2 = w_6 = 0.27970\ 53915$
$x_3 = -x_5 = 0.40584\ 51514$		$w_3 = w_5 = 0.38183\ 00505$
$x_4 = 0$		$w_4 = 0.41795\ 91837$
ξ_r	$n=8$, $k=4$	w_r
$x_1 = -x_8 = 0{,}96028\ 98565$		$w_1 = w_8 = 0{,}10122\ 85363$
$x_2 = -x_7 = 0{,}79666\ 64774$		$w_2 = w_7 = 0{,}22238\ 10345$
$x_3 = -x_6 = 0{,}52553\ 24099$		$w_3 = w_6 = 0.31370\ 66459$
$x_4 = -x_5 = 0.18343\ 46425$		$w_4 = w_5 = 0{,}36268\ 37834$
	$n=9$	
$x_1 = -x_9 = 0{,}96816\ 02395$		$w_1 = w_9 = 0{,}08127\ 43884$
$x_2 = -x_8 = 0{,}83603\ 11073$		$w_2 = w_8 = 0{,}18064\ 81607$
$x_3 = -x_7 = 0{,}61337\ 14327$		$w_3 = w_7 = 0{,}26061\ 06964$
$x_4 = -x_6 = 0{,}32425\ 34234$		$w_4 = w_6 = 0{,}31234\ 70770$
$x_5 = 0$		$w_5 = 0.33023\ 93550$
ξ_r	$n=10$, $k=5$	w_r
$x_1 = -x_{10} = 0{,}97390\ 65285$		$w_1 = w_{10} = 0.06667\ 13443$
$x_2 = -x_9 = 0{,}86506\ 33667$		$w_2 = w_9 = 0.14985\ 13492$
$x_3 = -x_8 = 0{,}67940\ 95683$		$w_3 = w_8 = 0.21908\ 63625$
$x_4 = -x_7 = 0{,}43339\ 53941$		$w_4 = w_7 = 0{,}26926\ 67193$
$x_5 = -x_6 = 0{,}14887\ 43399$		$w_5 = w_6 = 0{,}29552\ 42247$

$$S_{\omega z} \cong 2\pi\left\{\sum_{r=1}^{k} w_r \xi_r I_\omega^+(z,\xi_r) - \sum_{r=1}^{k} w_r \xi_r I_\omega^-(z,\xi_r)\right\}$$

We obtain the radiation flux in the infrared spectral region by summing over all frequency interval $\Delta\omega_i$ cm^{-1}

$$S(z) \cong \sum_i 2\pi\left\{\sum_{r=1}^{k} w_r \xi_r I_i^+(z,\xi_r)\Delta\omega_i - \sum_{r=1}^{k} w_r \xi_r I_i^-(z,\xi_r)\Delta\omega_i\right\}$$

The radiation intensities $I_i^{\pm}(z,\xi_r)$ averaged in the i-th frequency interval and appearing in this expression are defined by the system

of equations (3) for boundary conditions (2) for k values from Table 1. To select the number of nodes in the Gaussian formula satisfying the required precision, calculations were made for the values k = 2, 3, 4, 5. The increase in k from 3 to 4 changes the overall fluxes at all levels by less than 0.5%. This is valid for all the atmospheric compositions considered. A further increase in k only slightly refines the fluxes. We can assume the use of k = 4 in the calculations to be quite adequate. We introduce the /11
following notation:

$$
\begin{aligned}
&\tilde{w}_\tau = 2\cdot w_\tau \quad \Big(\sum_{\tau=1}^{k}\tilde{w}_\tau = 2\Big)\\
&\pi I_i^{\pm}(z,\xi_\tau)\,\Delta\omega_i = F_i^{\pm}(z,\xi_\tau)\\
&\pi I_{pi}(z)\,\Delta\omega_i = B_i(z)
\end{aligned}
$$

Here B_i has a clear physical significance. This is the one-way flux of equilibrium radiation in the interval $\Delta\omega_i$. In this notation scheme we have,

$$
\begin{aligned}
S(z) &= \sum_i\sum_\tau\big\{\tilde{w}_\tau\xi_\tau F_i^{+}(z,\xi_\tau) - \tilde{w}_\tau\xi_\tau F_i^{-}(z,\xi_\tau)\big\}\\
F_i^{\pm}(z,\xi_\tau) &= B_i(z) + \big[F^{\pm}(z_0^{\pm},\xi_\tau) - B_i(z_0^{\pm})\big]\tau_i(z_0^{\pm},z,\xi_\tau) - \\
&\quad - \int_{z_0^{\pm}}^{z}\tau_i(z',z,\xi_\tau)\,dB_i(z')\\
F_i^{\pm}(z_0^{\pm},\xi_\tau) &= \varepsilon^{\pm}B_i(z_0^{\pm}) + (1-\varepsilon^{\pm})\,\frac{\sum_{\tau=1}^{k}\tilde{w}_\tau\xi_\tau F_i^{\mp}(z_0^{\pm},\xi_\tau)}{\sum_{\tau=1}^{k}\tilde{w}_\tau\xi_\tau}
\end{aligned}
$$

As shown by the calculations whose results are illustrated by Fig.s 7 and 8, the one-way fluxes integral over the infrared spectrum depend only slightly on the atmospheric composition for the optically dense subcloud atmosphere of Venus, especially in models containing water vapor, and are close to the one-way flux of equilibrium radiation reflecting the temperature trend in the atmosphere. To avoid calculation of the exiting flux as the difference of two similar in magnitude and larger one-way fluxes it is useful to introduce the following quantities:

$$\Delta F_i^{\pm}(z,\xi_r) = F_i^{\pm}(z,\xi_r) - B_i(z)$$

Then:

$$\mathcal{F}(z) \cong \sum_i \left\{ \sum_{r=1}^{k} \tilde{w}_r \xi_r \Delta F_i^{+}(z,\xi_r) - \sum_{r=1}^{k} \tilde{w}_r \xi_r \Delta F_i^{-}(z,\xi_r) \right\}$$

The differences ΔF_i^{+} and ΔF_i^{-} are defined by the system: /12

$$\Delta F_i^{\pm}(z,\xi_r) = \Delta F_i^{\pm}(z_0^{\pm},\xi_r)\,\tau_i(z_0^{\pm},z,\xi_r) - \int_{z_0^{\pm}}^{z} \tau_i(z',z,\xi_r)\,dB_i(z')$$

which we will solve given the boundary conditions

$$\Delta F_i^{\pm}(z_0,\xi_r) = (1-\varepsilon^{\pm})\,\frac{\sum_{r=1}^{k} \tilde{w}_r \xi_r \Delta F_i^{\mp}(z_0^{\pm},\xi_r)}{\sum_{r=1}^{k} \tilde{w}_r \xi_r}$$

If the blackbody factor of the lower surface of the cloud layer $\varepsilon_c = \varepsilon^-$ (when $Z_0^- = H$) or the blackbody factor the planetary surface $\varepsilon_s = \varepsilon^+$ (for $Z_0^+ = 0$) is equal to 1, the system becomes solvable. Given the condition that both surfaces can be regarded as absolutely black, the last system reduces to the following expressions:

$$\Delta F_i^{+}(z,\xi_r) = -\int_0^{z} \tau_i(z',z,\xi_r)\,dB_i(z')$$

$$\Delta F_i^{-}(z,\xi_r) = -\int_H^{z} \tau_i(z',z,\xi_r)\,dB_i(z')$$

In this case the exiting flux is defined as:

$$\mathcal{F}(z) = -\sum_i \sum_{r=1}^{k} \tilde{w}_r \xi_r \int_0^{H} \tau_i(z',z,\xi_r)\,dB_i(z')$$

To calculate the distribution of thermal radiation fluxes, the subcloud atmosphere at altitude H was divided into a layer 2 km thick . by the altitude coordinates Z_j ($j = 0, 1, \ldots, N$). Then we will have the following relations for the j-th level (we omit the subscript i). For integration from the top, we have:

$$\Delta F^{+}(z_0,\xi_\tau)=(1-\varepsilon_g)\frac{\sum_{\tau=1}^{k}\tilde{w}_\tau \xi_\tau \Delta F^{-}(z_0,\xi_\tau)}{\sum_{\tau=1}^{k}\tilde{w}_\tau \xi_\tau}$$

$$\Delta F^{+}(z_j,\xi_\tau)=\Delta F^{+}(z_0,\xi_\tau)\tau(z_0,z_j,\xi_\tau)-\int_{z_0}^{z_j}\tau(z',z_j,\xi_\tau)\,dB(z')$$
$$j=1,2,\ldots,N.$$

For integration from beneath, we have /13

$$\Delta F^{-}(z_N,\xi_\tau)=(1-\varepsilon_c)\frac{\sum_{\tau=1}^{k}\tilde{w}_\tau \xi_\tau \Delta F^{+}(z_N,\xi_\tau)}{\sum_{\tau=1}^{k}\tilde{w}_\tau \xi_\tau}$$

$$\Delta F^{-}(z_j,\xi_\tau)=\Delta F^{-}(z_N,\xi_\tau)\tau(z_N,z_j,\xi_\tau)-\int_{z_N}^{z_j}\tau(z',z_j,\xi_\tau)\,dB(z')$$
$$j=N-1,N-2,\ldots,0.$$

Since the transmission functions in the i-th frequency interval were calculated in the weak line approximation, which yields the following exponential function:

$$\tau_i(z_1,z_2,\xi)=\exp\left(-\left|\int_{z_1}^{z_2}\frac{k_i(z'')}{\xi}\,dz''\right|\right),$$

then the following relation is satisfied for arbitrary $Z_1 < Z_2 < Z_3$:

$$\tau_i(z_1,z_3)=\tau_i(z_1,z_2)\cdot\tau_i(z_2,z_3)$$

With this property taken into account, we can integrate successively from level to level, using the already found $\Delta F^{\pm}$ for the preceding level. We thus show, for example that for ΔF^{+} we have:

$$\Delta F^{+}(z_j) = \Delta F^{+}(z_0)\tau(z_0, z_j) - \int_{z_0}^{z_j} \tau(z', z_j)\, dB(z') =$$

$$= \Delta F^{+}(z_0)\tau(z_0, z_{j-1})\tau(z_{j-1}, z_j) - \int_{z_0}^{z_{j-1}} \tau(z', z_{j-1})\tau(z_{j-1}, z_j)\, dB(z') -$$

$$- \int_{z_{j-1}}^{z_j} \tau(z', z_j)\, dB(z') =$$

$$= \left\{ \Delta F^{+}(z_0)\tau(z_0, z_{j-1}) - \int_{z_0}^{z_{j-1}} \tau(z', z_{j-1})\, dB(z') \right\} \tau(z_{j-1}, z_j) -$$

$$- \int_{z_{j-1}}^{z_j} \tau(z', z_j)\, dB(z')$$

But the expression in the braces is $\Delta F^{+}(Z_{j-1})$. And thus, /14

$$\Delta F^{+}(z_j) = \Delta F^{+}(z_{j-1})\tau(z_{j-1}, z_j) - \int_{z_{j-1}}^{z_j} \tau(z', z_j)\, dB(z')$$

Finally, we will have the following system:
For integration from above:

$$\Delta F_i^{+}(z_0, \xi_r) = (1 - \varepsilon_s) \frac{\sum_{r=1}^{k} \tilde{w}_r \xi_r \Delta F_i^{-}(z_0, \xi_r)}{\sum_{r=1}^{k} \tilde{w}_r \xi_r}$$

$$\Delta F_i^{+}(z_j, \xi_r) = \Delta F_i^{+}(z_{j-1}, \xi_r)\tau_i(z_{j-1}, z_j, \xi_r) - \int_{z_{j-1}}^{z_j} \tau_i(z', z_j, \xi_r)\, dB_i(z')$$

$$j = 1, 2, \ldots, N.$$

For integration from beneath, we have

$$\Delta F_i^-(z_N, \xi_\tau) = (1-\varepsilon_c)\frac{\sum_{\tau=1}^{k}\tilde{\omega}_\tau \xi_\tau \Delta F_i^+(z_N, \xi_\tau)}{\sum_{\tau=1}^{k}\tilde{\omega}_\tau \xi_\tau}$$

$$\Delta F_i^-(z_j, \xi_\tau) = \Delta F_i^-(z_{j+1}, \xi_\tau)\tau_i(z_{j+1}, z_j, \xi_\tau) - \int_{z_{j+1}}^{z_j}\tau_i(z', z_j, \xi_\tau)dB_i(z')$$

$$j = N-1, N-2, \ldots, 0.$$

Let Z_h denote the level at which we already know the value of ΔF_h^+ or ΔF_h^-, and let Z_k represent the level at which we seek ΔF_k^+ or ΔF_k^- based on this already known value. Then for integration from above and from beneath, the computation will be made based on the following formula:

$$\Delta F_{ik}(z_k, \xi_\tau) = \Delta F_{ih}(z_h, \xi_\tau)\tau_i(z_h, z_k, \xi_\tau) - \int_{z_h}^{z_k}\tau_i(z', z_k, \xi_\tau)dB_i(z') \qquad (4)$$

The transmission functions were calculated thusly. First of all, the absorption coefficients were found for atmospheric gas for the temperature and pressure parameters at all levels Z_j ($j = 0, 1, \ldots N$);

$$k_j = k_j(P(z_j), T(z_j));$$

$$k_j = k_{CO_2}(P_j, T_j)\frac{P_{CO_2}}{P} + k_{H_2O}(P_j, T_j)\, P_{H_2O}/P$$

For CO_2: /15

based on the values of $(s/d)_{STP}$ reduced to STP conditions for the intervals $\Delta\omega_i = 10\ \text{cm}^{-1}$ in the CO_2 bands for 11 temperature values from 295 to 800°K, with a 50°K step, we found the s/d values for $T = T_j$ by linear integration of the tabulated values of $\ln(s/d)_{STP}$, and further:

$$k_j(T_j, P_j) = s/d\,(T_j)\cdot\frac{273}{T_j}\, P_j$$

In the spectral regions where the induced 7.5 μm band is superposed to this coefficient the following was added:

$$K_{7.5}(294)\left(\frac{294}{T}\right)^5 p_j^2$$

To the quanta of the 4.3 and 2.7 μm bands were added the following:

$$\frac{295}{273}\,\tilde{K}(295)\,\frac{K_{max}(T_j, p_j)}{K_{max}(295, p=1)}\cdot\left(\frac{273}{T_j}\,p_j\right)^2$$

For H_2O:

for absorption coefficients, reduced to STP conditions, for the temperatures 300, 600 and 1000°K, we found the $K(T_j)$ values by quadratic interpolation of the tabulated values of $\ln(K)_{STP}$ and then:

$$K_j(p_j, T_j) = K(T_j)\,\frac{273}{T_j}\,p_j$$

It was further assumed that within each layer the temperature and the natural logarithm of the absorption coefficient of the atmospheric gas vary linearly with altitude. Given these assumptions, the transmission functions appearing in formula (4) will be expressed in finite form.

$$\tau(z_H, z_K, \xi_r) = \exp\left\{-\left|\int_{z_H}^{z_K}\frac{K(z'')}{\xi_r}\,dz''\right|\right\} = $$ /16

$$= \exp\left\{-\left[\frac{K_K - K_H}{\ln K_K/K_H}\cdot\frac{|z_K - z_H|}{\xi_r}\right]\right\} = \exp(-D);$$

where D is the optical thickness of the layer between the levels Z_H and Z_K in the direction to which the cosine of the zenith angle is ξ_r. Then, for Z' varying within the limits we have

$$\tau(z', z_K, \xi_z) = \exp\left\{-\left|\int_{z'}^{z_K} \frac{K(z'')}{\xi_z} dz''\right|\right\} = \exp(-D \cdot \alpha);$$

where:

$$\alpha = \alpha(T') = \frac{1 - \left(\frac{K_H}{K_K}\right)^{\frac{T_K - T'}{T_K - T_H}}}{1 - K_H/K_K};$$

$$T' = T(z'); \quad 0 \leq \alpha \leq 1;$$

For the case when the conditions are homogeneous in the layer and, therefore, $K_H = K_K = K$, the expressions for D and α pass to the limit:

$$D = K \cdot \frac{|z_K - z_H|}{\xi_z}$$

$$\alpha = (T_K - T')/(T_K - T_H) = (z_K - z')/(z_K - z_H)$$

The integral appearing in expression (4) will now become:

$$\int_{z_H}^{z_K} \tau_i(z', z_K, \xi_z) dB_j = \int_{T_H}^{T_K} \exp[-D_i \cdot \alpha_i(T')] \frac{dB_i}{dT}(T')\, dT'$$

Integration was carried out by the Simpson method with automatic selection of the step based on the assigned relative precision. The results presented above were obtained for a 1% precision. /17
Control calculations showed that reducing this value only slightly refines the distribution of overall fluxes. The problem was solved on a BESM-6 computer.

In the calculations we used CO_2 absorption coefficients in the region 130-8310 cm^{-1}. The overall one-way flux of an absolute black body surface at the temperature T_s = 750°K is more than 99% of the total value (σT_s^4) in this spectral region. From Fig. 5 it is also clear that in the region 130-6000 cm^{-1} the surface radiates 99.6% of the energy. Therefore generally the calculations of the thermal radiation fluxes were made for the spectral region to 6000 cm^{-1} with a 25 cm^{-1} step. Here the initial absorption coefficients for CO_2 calculated for 10 cm^{-1} intervals were averaged. Model compositions of the Venusian atmosphere were investigated as follows: an atmosphere of pure CO_2, and also atmosphere containing 97% CO_2 and H_2O vapor in the range 0.002 to 1%. The effect of N_2, whose content generally speaking can be as much as 2% [1], on the absorbing characteristics of the atmosphere was neglected. The spectral region considered was extended due to the H_2O absorption coefficients, beginning at 50 cm^{-1}. Fig. 6 shows the distribution of fluxes by altitude in the region 6000 cm^{-1} to 8310 cm^{-1} for several atmospheric compositions. The values of these fluxes are no more than 2% of those that are transferred to the region up to 6000 cm^{-1}. It must be noted that we did not have available data on the absorption coefficients beyond the quanta of the 1.4 and 1.2 μm bands. Therefore the fraction of thermal radiation transferred in the 6000-8310 cm^{-1} short-wave region will be even smaller. The altitude distribution /18 of the one-way fluxes integral over the spectrum are shown in Fig.s 7 and 8 for various atmospheric compositions. With increase in the H_2O content in the atmosphere, these functions approximate the distribution of the one-way flux of equilibrium radiation reflecting the temperature trend in the atmosphere and differ little for the values of relative content considered. This shows the high optical density of the atmosphere. Exiting radiation fluxes, which represent the difference in one-way fluxes of large magnitude were determined by transfer only in some narrow transparency "windows," in which absorption coefficients depend strongly on the relative H_2O content. Hence follows the substantial difference in the nature of the distribution and in the values of the exiting thermal radiation fluxes for atmosphere models composed of CO_2 and H_2O, differing in the H_2O content as shown in Fig. 9. These results were obtained on the assumption that the surface of the planet and the clouds radiate like a blackbody ($\varepsilon_s = \varepsilon_c = 1$). If we estimate the mean energy flux from the sun reaching a rotating planet based on the formula $E(1 - A)/4$, then for the solar constant value for Venus, $E = 3.83$ cal/cm^2·min, we obtain the following values for the integral spherical albedo of the planet currently adopted, $A = 0.77 \pm 0.07$ (Irvine, 1968):

$E(1-A)$	:	$615 \cdot (1 \mp 0.3)$ W/m^2
$E(1-A)/4$	:	$154 \cdot (1 \mp 0.3)$ W/m^2
$T_e = \sqrt[4]{\frac{E(1-A)}{4\sigma}}$	:	$228\ ^\circ K \mp 17\ ^\circ K$

From Fig. 9 we see that in an atmosphere of pure CO_2, or containing /19
0.001% H_2O thermal radiation fluxes at all levels significantly exceed those arriving from the sun and become comparable or smaller if we assume the H_2O content $\gtrsim$ 0.1%. Figs. 9-13 give, in their upper sections, the values for the effective temperature $T_e = \sqrt[4]{S/\sigma}$, corresponding to radiative fluxes of the X-axis. Fig. 10 gives the flux distributions by altitude for the following H_2O content values: 0.1, 0.2, 0.3, 0.5, and 1%. The effective temperature of 228°K corresponding to the mean inflow of solar energy to the planet for the albedo A = 0.77 can be provided by just the radiative thermal fluxes of the atmosphere for a H_2O content ~0.1%. It must be noted that in spite of the variability of fluxes by altitude, their variation is within the limits 15% for all the compositions considered with H_2O content 0.1 to 1%.

The distribution of radiative fluxes for the case of reflecting clouds is given in Figs. 11-13. Fig. 11 shows the effect of the blackbody factor of the lower cloud surface ε_c for an atmosphere of pure CO_2. Since the radiation of the black surface is low at the cloud temperature, the exiting flux at the cloud level is reduced by about twofold for $\varepsilon_c = 0.5$, and when $\varepsilon_c = 0.1$ -- by 10 times compared with the case $\varepsilon_c = 1$. The overall level of the fluxes is also reduced. However, the maximum value of the fluxes are reduced only by 15% when $\varepsilon_c = 0.5$, and by 26% when $\varepsilon_c = 0.1$. Also shown in these figures is the effect of a planetary surface with a blackbody factor ε_s distinct from one. Reducing ε_s from 1 to 0.5 leads to only an 11% reduction in maximum fluxes. A similar trend is noted for the variation in flux distribution by altitude for reflecting clouds compared with absolutely black clouds in an atmosphere containing H_2O, which is shown in Figs. 12-13.

The successive contribution of individual spectral regions /20
to the overall flux in the infrared spectral region is shown in Figs. 14-18 for various models of atmospheric composition. For the models of greatest interest with H_2O content $\gtrsim$ 0.1%, the spectral interval 50 - 3450 cm^{-1} makes a contribution to the flux principally above 30 km. A substantial contribution of the overall flux is provided by the spectral region between the 2.7 and 2.0 μm CO_2 bands, and more exactly -- beyond the quanta of these bands. It must be emphasized that these results were obtained without excluding any spectral regions in the range 50-6000 cm^{-1}. Then, by a direct comparison with the values of overall fluxes in this entire range, we isolated spectral "windows" in which generally speaking radiation is transferred in an atmosphere consisting of 97% CO_2 and H_2O in the range 0.1-1%. The entire thermal flux is transferred in the following "windows," with a precision up to fractions of a percent:

1. 30- 550 cm^{-1}
2. 800-2225 cm^{-1} (99% up to 1400 cm^{-1})
3. 2550-3350 cm^{-1}
4. 4050-4650 cm^{-1}
5. 5600-600 cm^{-1}

Figs. 19 and 20 show the successive contributions of these windows to radiation transfer for H_2O content values of 0.1% and 0.3%.

The 300 - 550 cm^{-1} "window" makes a contribution only above 50 km and amounts to not more than 3% of the overal flux.

In the 800-2225 cm^{-1} interval, the radiation is mainly transferred at elevations greater than 30 km and amounts to 30% (1% H_2O) to 40% (0.1% H_2O) of the total flux, near the clouds. It must be noted that 99% of the radiation in this "window" is transferred in the 800 - 1400 cm^{-1} interval. Here transfer is determined in the 800 - 1100 cm^{-1} interval mainly by the 15 μm and 9.4-10.4 μm CO_2 bands, and in the 1125 - 1400 cm^{-1} interval /21
-- by the induced 7.5 μm CO_2 band and by the contribution of H_2O to absorption.

The 2250 - 3350 cm^{-1} "window" between the 4.3 and 2.7 μm CO_2 bands contributes at altitudes below 30 km and amounts to not more than 10%.

The most substantial contribution is made by the 4050 - 4650 cm^{-1} "window" between the 2.7 and 2.0 μm CO_2 bands: the upper half of the subcloud atmosphere accounts for more than 60%, with an increase in this proportion with greater proximity to the planetary surface.

The 5600 - 6000 cm^{-1} "window" between the 2.0 and 1.0 μm band adds several percentage points to the total flux over the entire altitude range.

The absorption characteristics for the atmosphere of Venus require further refinement. Based on the calculations made, it can be concluded that this will involve primarily those spectral regions in which, besides H_2O, contributions come from the quanta of the CO_2 bands, the hot transitions of the CO_2 bands, and also the induced absorption in the 7.5 μm band. The question as to what errors will result from calculating transmission functions in the weak line approximation over the entire range of variation in T and P by altitude remains thus far open.

From the results of the calculations, the following conclusions can be made with a precision up to the absorption characteristics used in the work.

In an atmosphere of pure CO_2, given the physical conditions of Venus beneath the clouds and with the integral albedo of the planet $A = 0.77 \pm 0.07$, the exiting thermal radiation flux at all altitudes considerably exceeds the mean inflow of solar energy. The presence of H_2O in the atmosphere considerably reduces the flux levels. However, for a relative H_2O content of 10^{-5}, the balance still cannot be achieved.

We cannot neglect the effect on the altitude distribution of fluxes of the possibility that the blackbody factor of the planet and cloud surface differs from 1. For the case of clouds reflecting in the infrared spectral region, the exiting flux at their level may correspond to the mean incoming solar energy, even in an atmosphere of pure CO_2 or containing 10^{-5} H_2O, though this necessitates an improbable reflectivity. However, the maximum fluxes decrease only slightly on this assumption, compared with the case of nonreflecting clouds, and the balance in depth cannot be reached. The contribution of the planetary surface to the exiting radiation is low, and even a significant difference in its blackbody factor from 1 has only a small effect on the exiting radiation at any altitude. /22

The exiting flux of thermal radiation can be reconciled, on the average, with the flux arriving from the sun for a planetary albedo A = 0.77 and smaller if the relative H_2O content in the atmosphere $\sim$0.1%, which radio astronomical measurements yield for the lower troposphere.

In these cases of greatest interest, the thermal radiation flux varies strongly with altitude. A sharp rise in the flux with altitude in the layer from the surface at 10 km can be accounted for by a reduction in the atmospheric opaqueness with decreasing T and P. The inversion trend in the range 10-30 km is difficult to explain if we do not bring in artificial assumptions. The window between the 2.7 and 2.0 μm CO_2 bands is a spectral region responsible mainly for this altitude trend of exiting radiation in the entire infrared spectrum. However, the flux variations noted are in the limits of 15% and it cannot be excluded that they are related to features of the assumed absorption characteristics of the CO_2 and H_2O mixture.

Further refinement of the thermal regime of the subcloud atmosphere of Venus will be obtained on the basis of results of illumination measurements made on the Venera 8 Interplanetary Automatic Station using revised characteristics of atmospheric absorption. /23

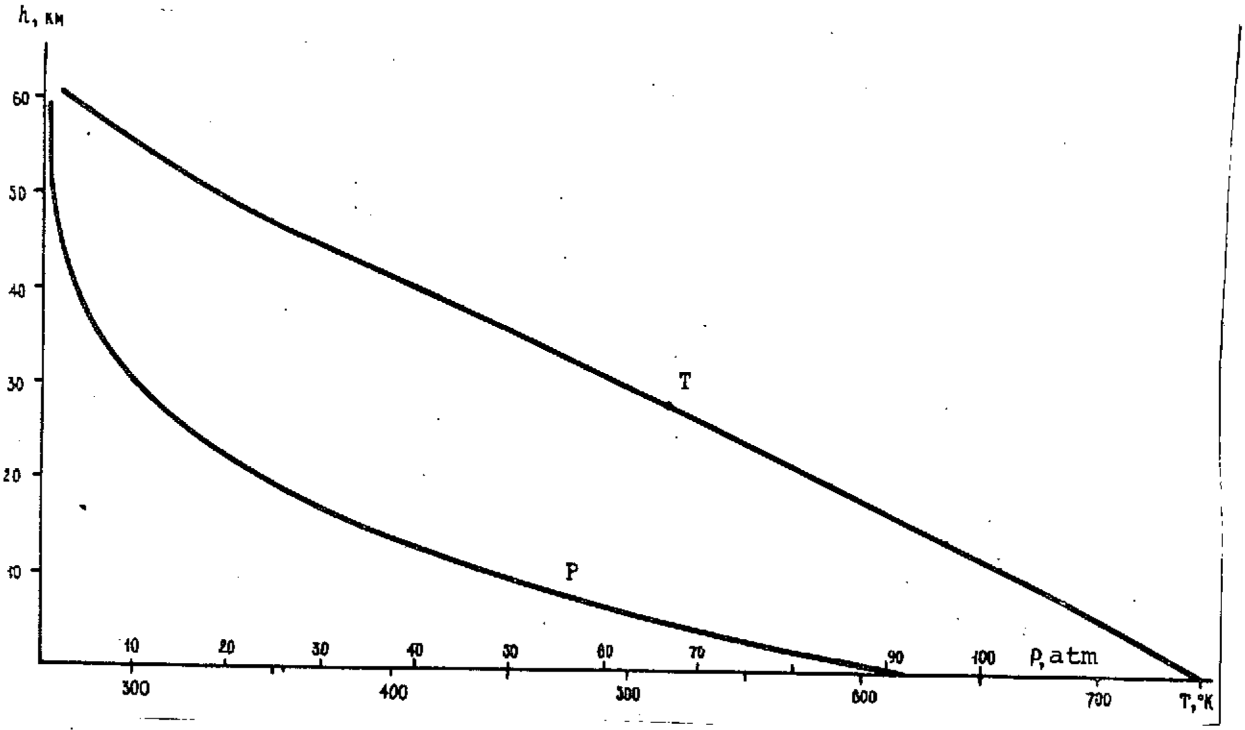

Fig. 1. /25

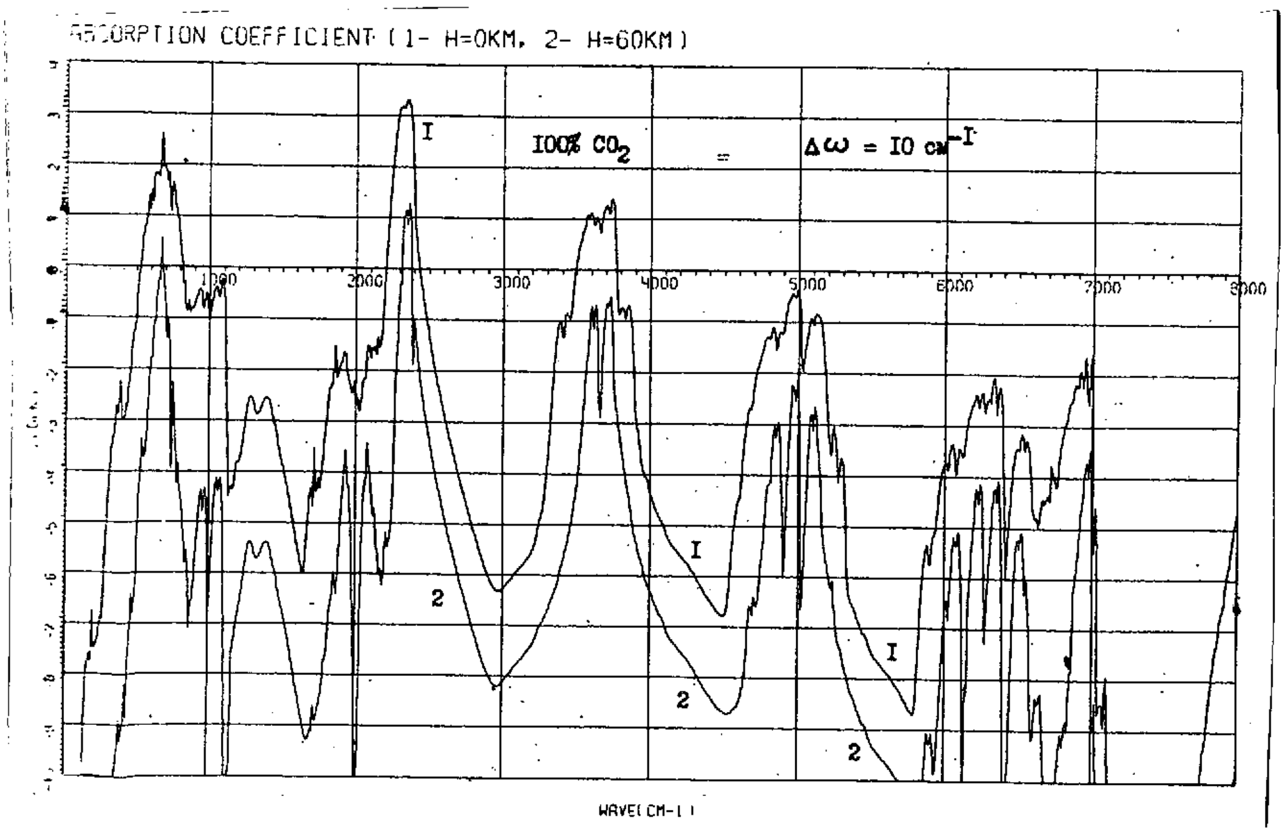

Fig. 2. /26

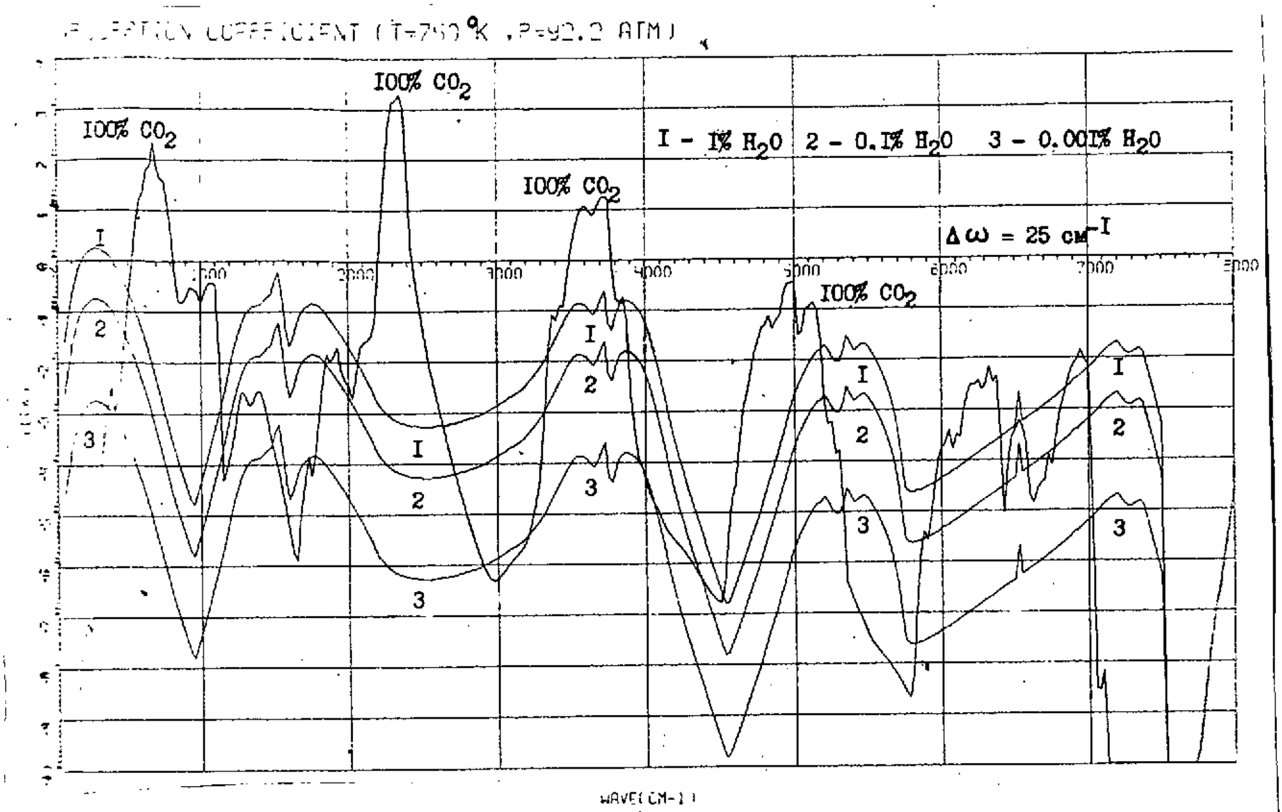

Fig. 3.

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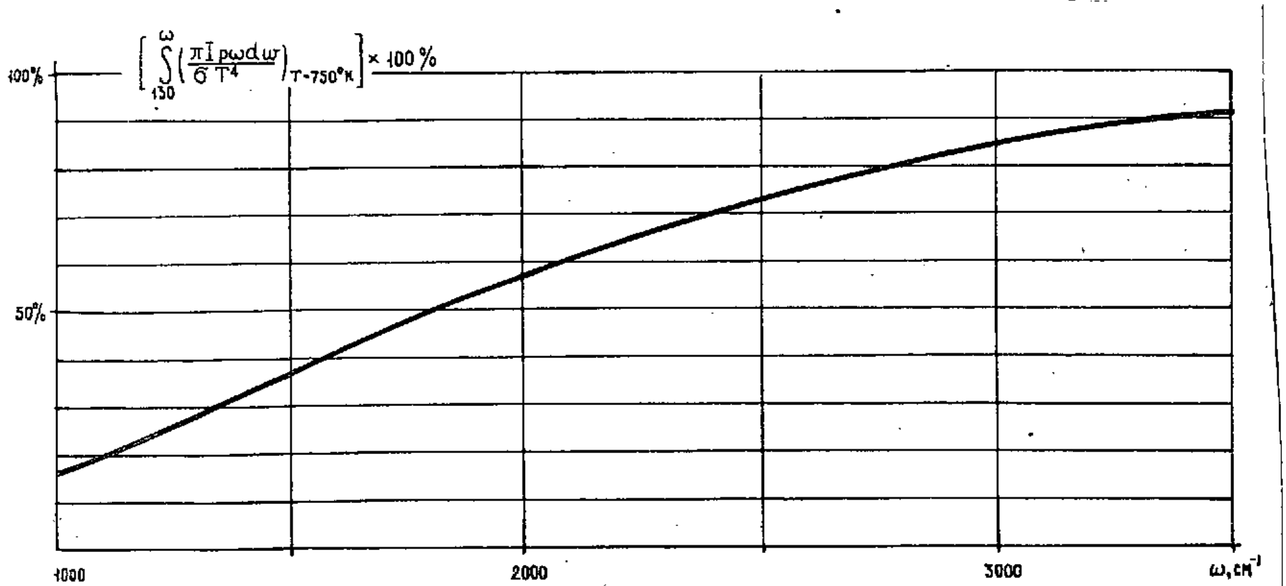

Fig. 4.

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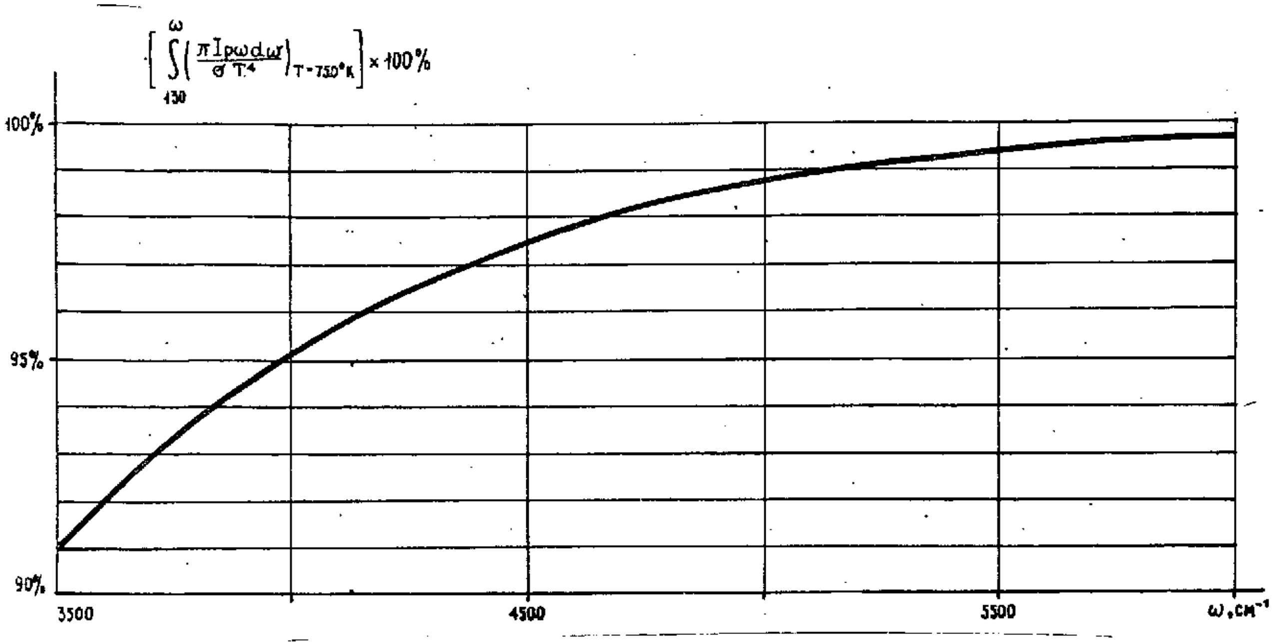

Fig. 5. /29

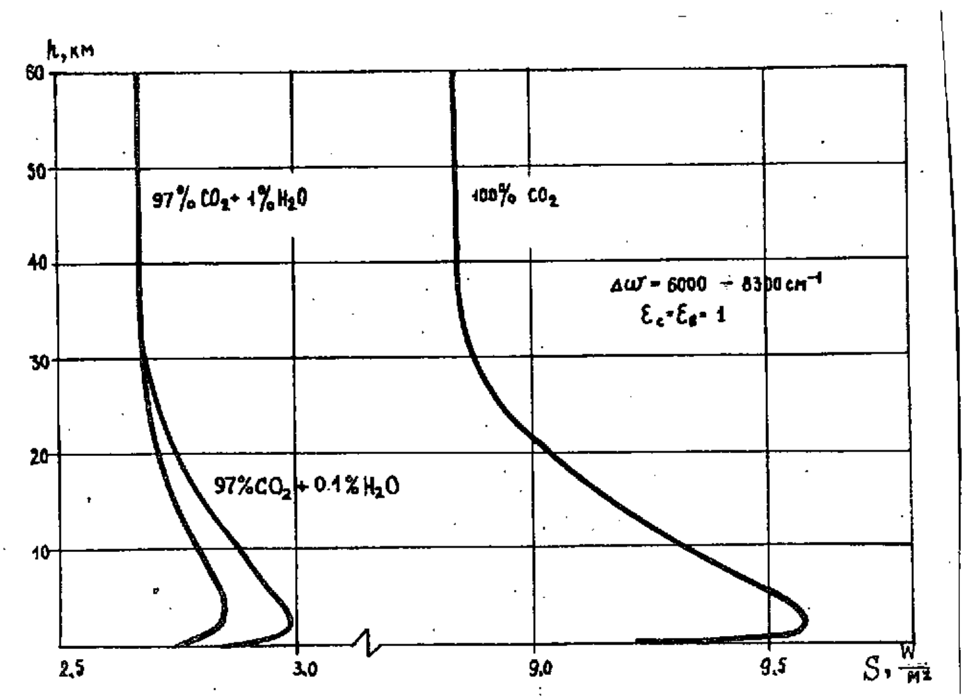

Fig. 6. /30

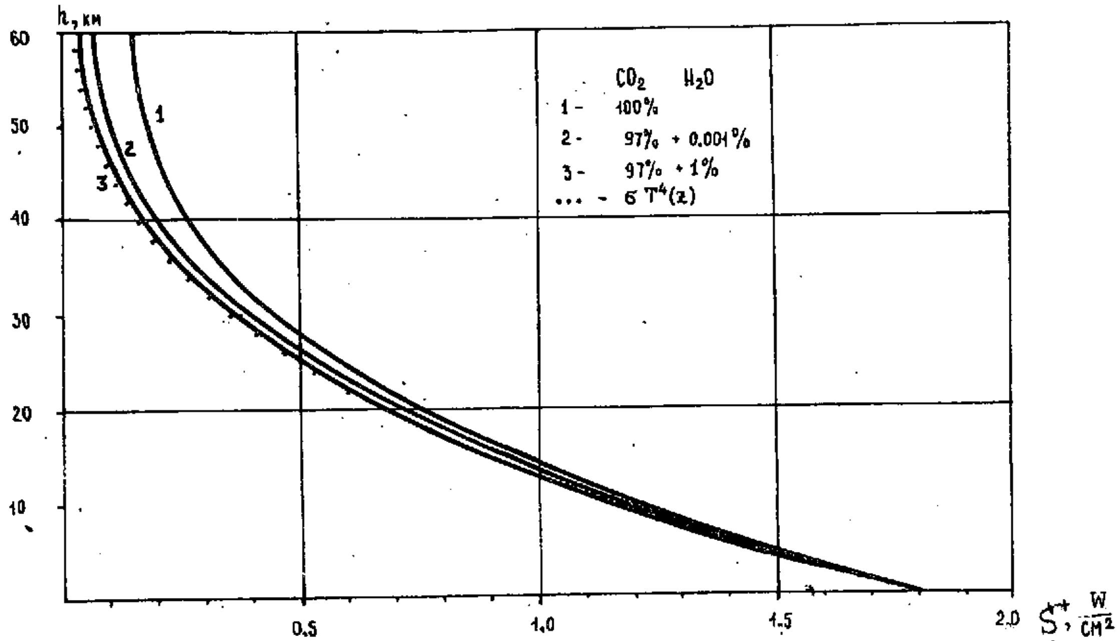

Fig. 7.

/31

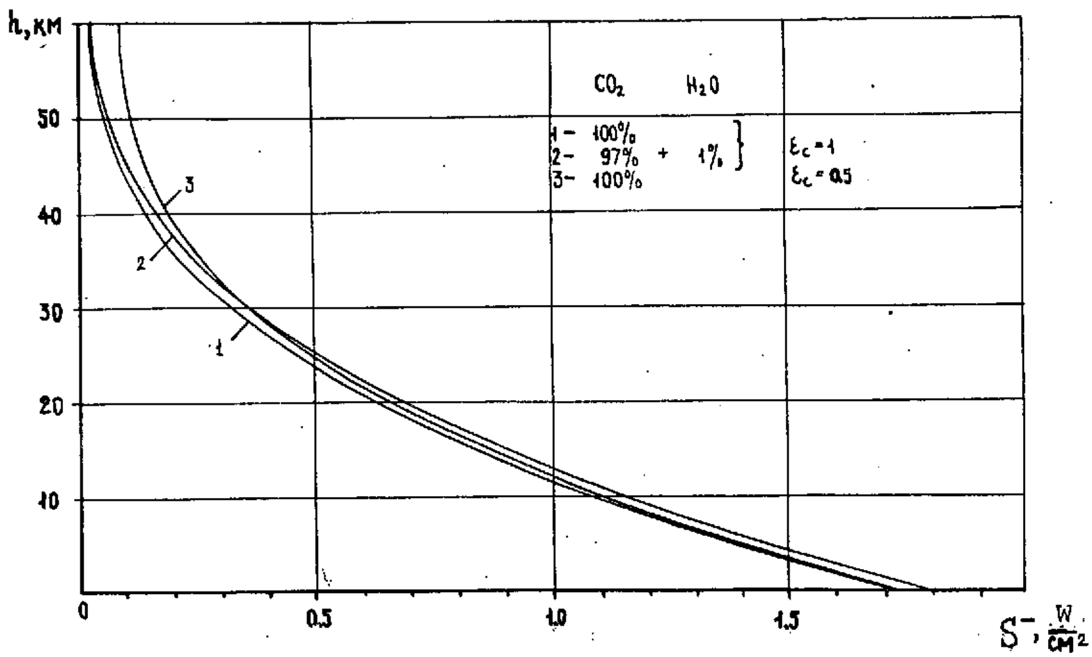

Fig. 8.

/32

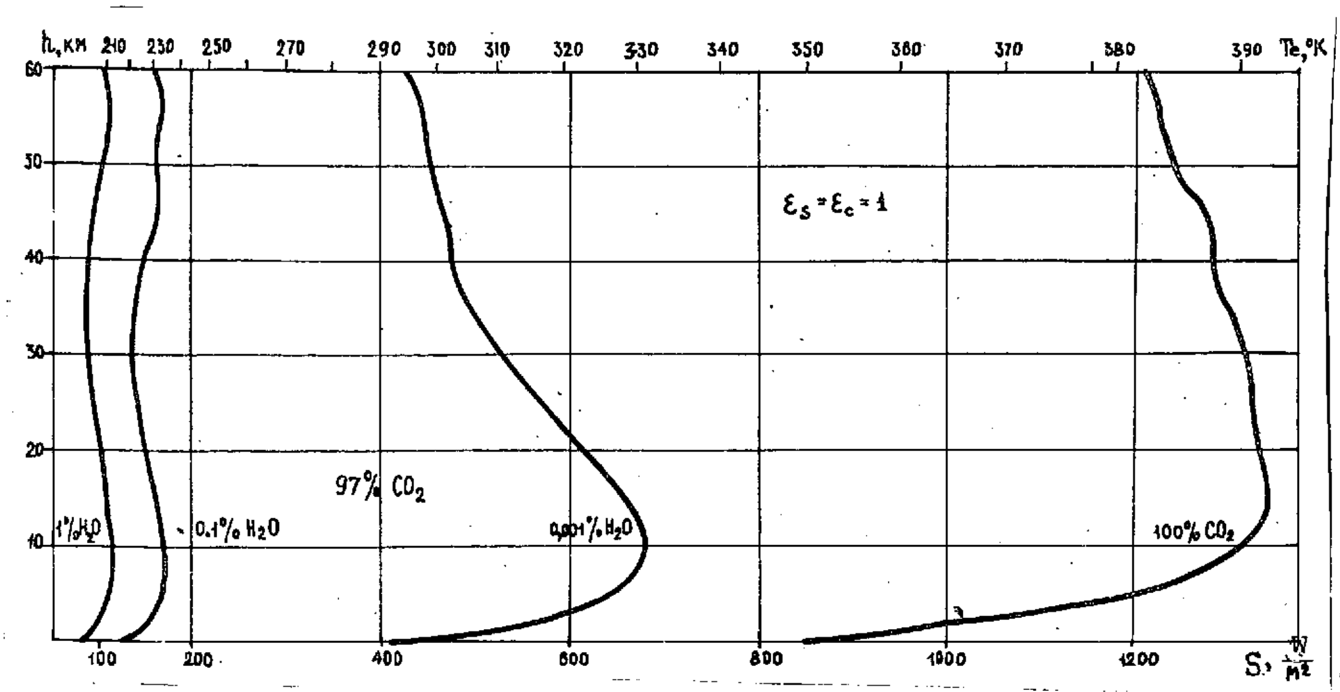

Fig. 9. /33

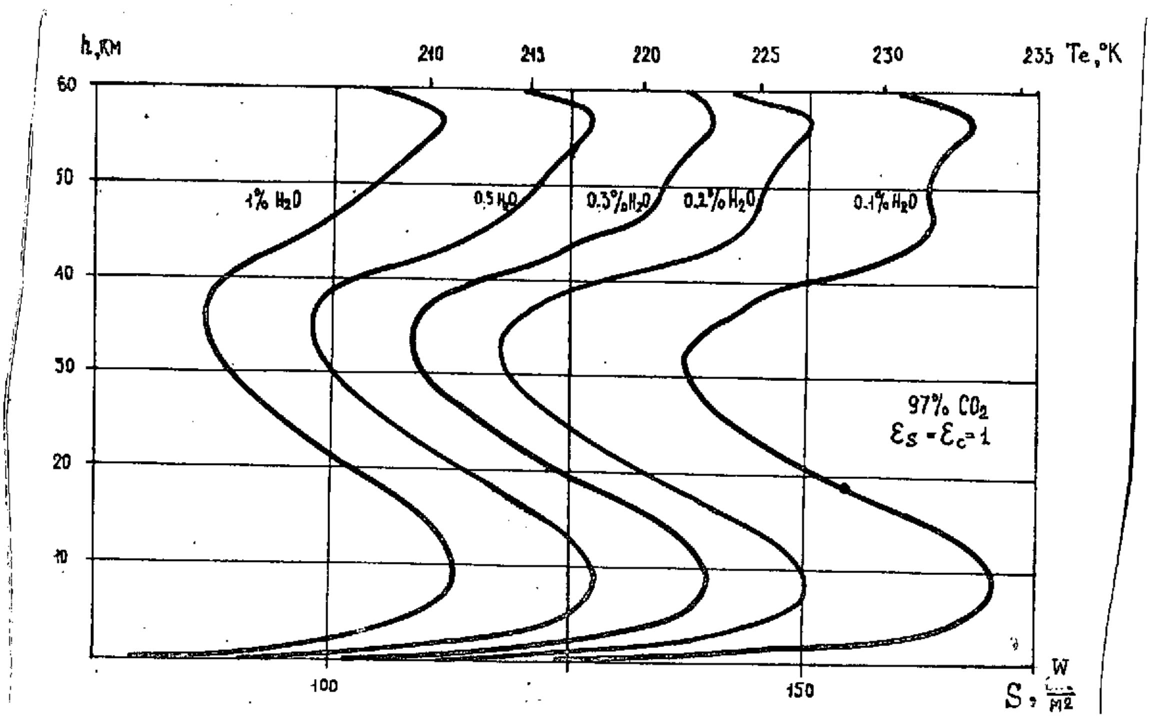

Fig. 10. /34

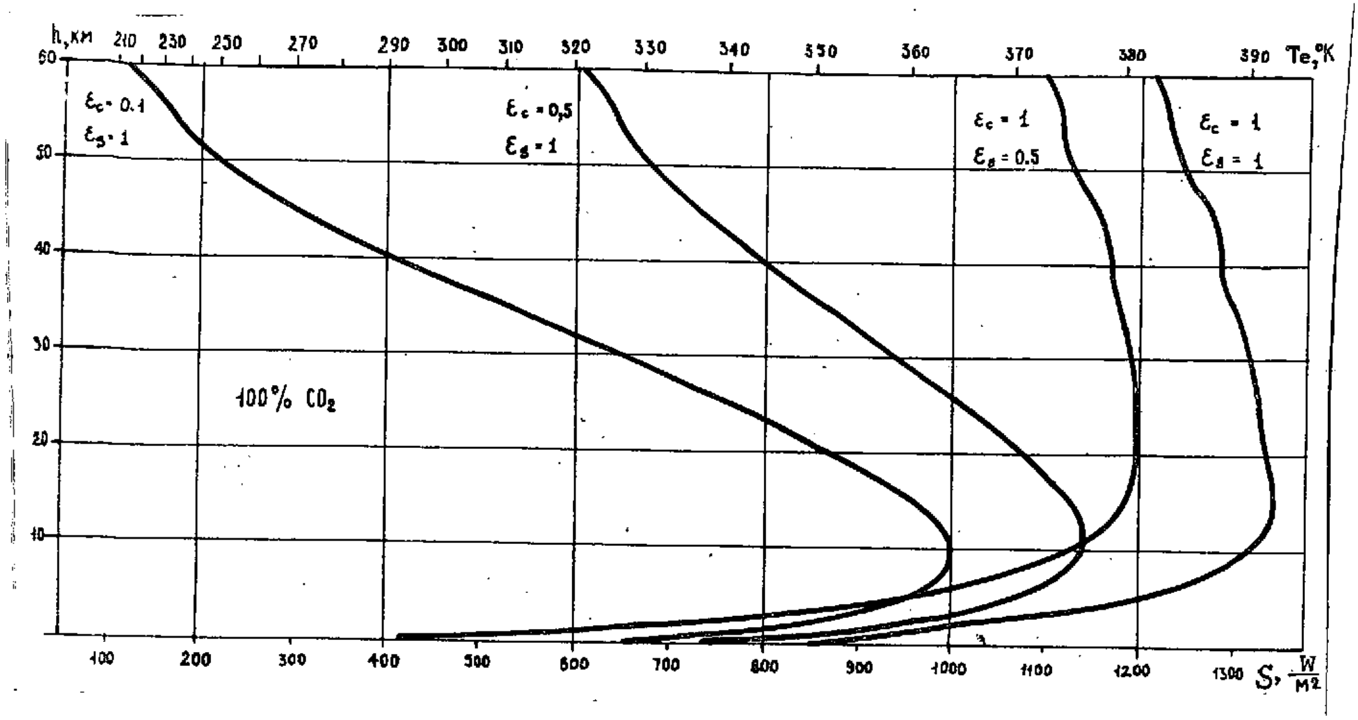

Fig. 11. /35

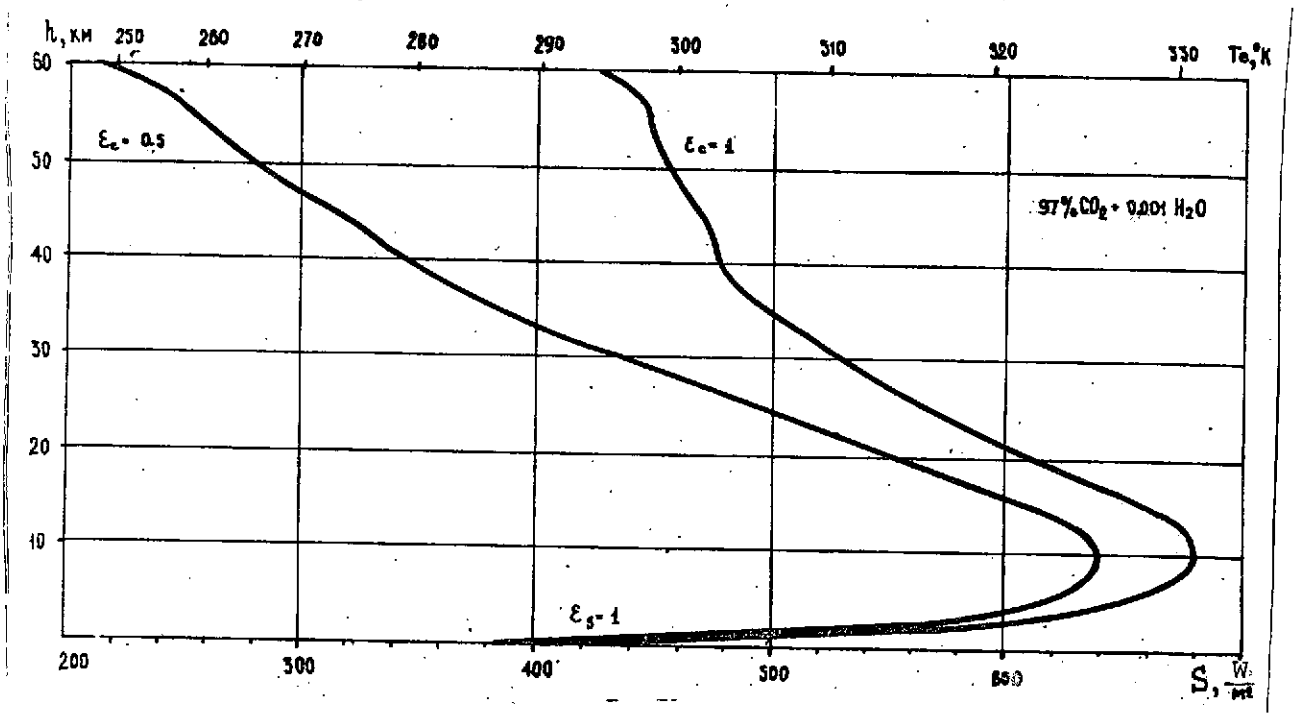

Fig. 12. /36

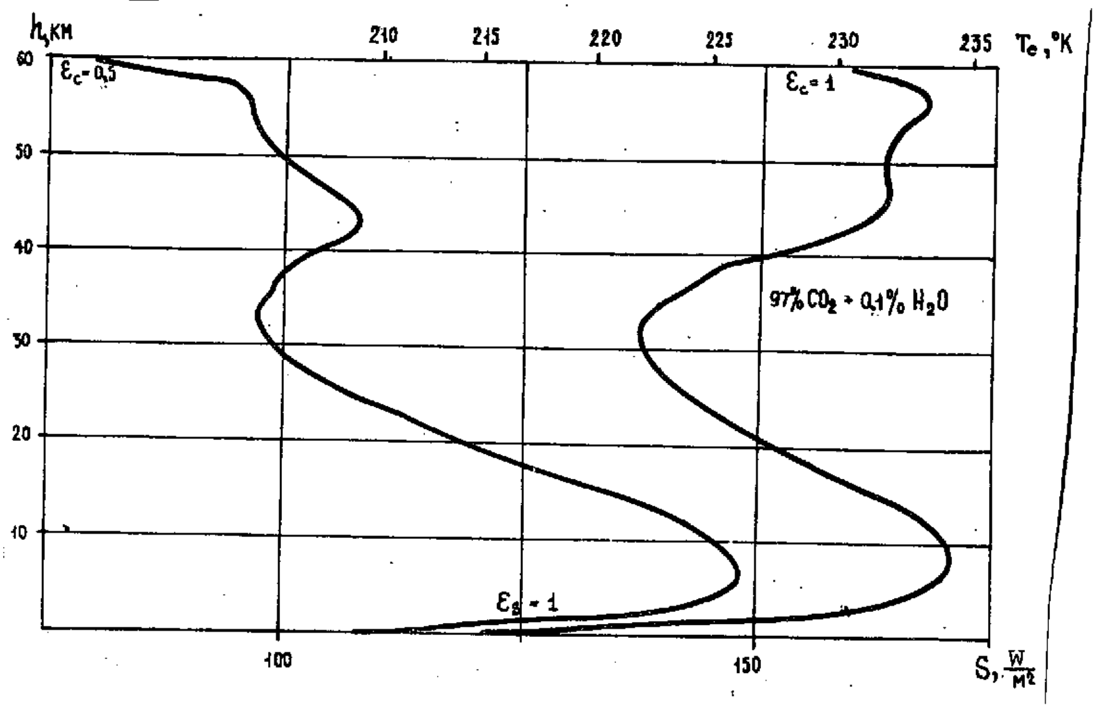

Fig. 13. /37

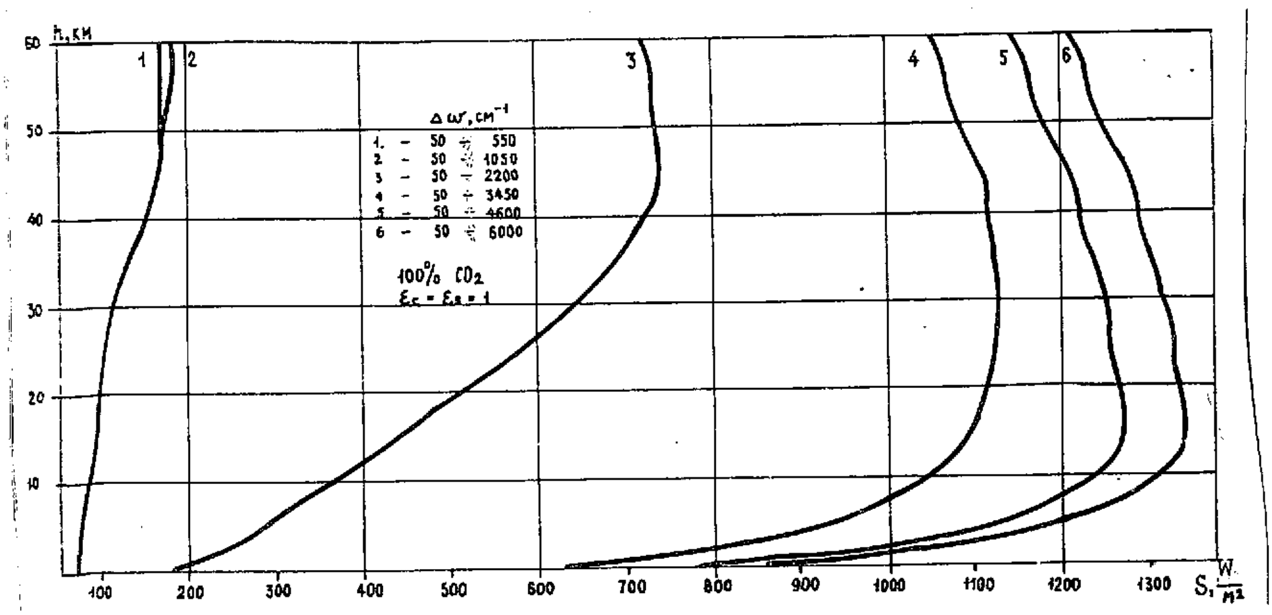

Fig. 14. /38

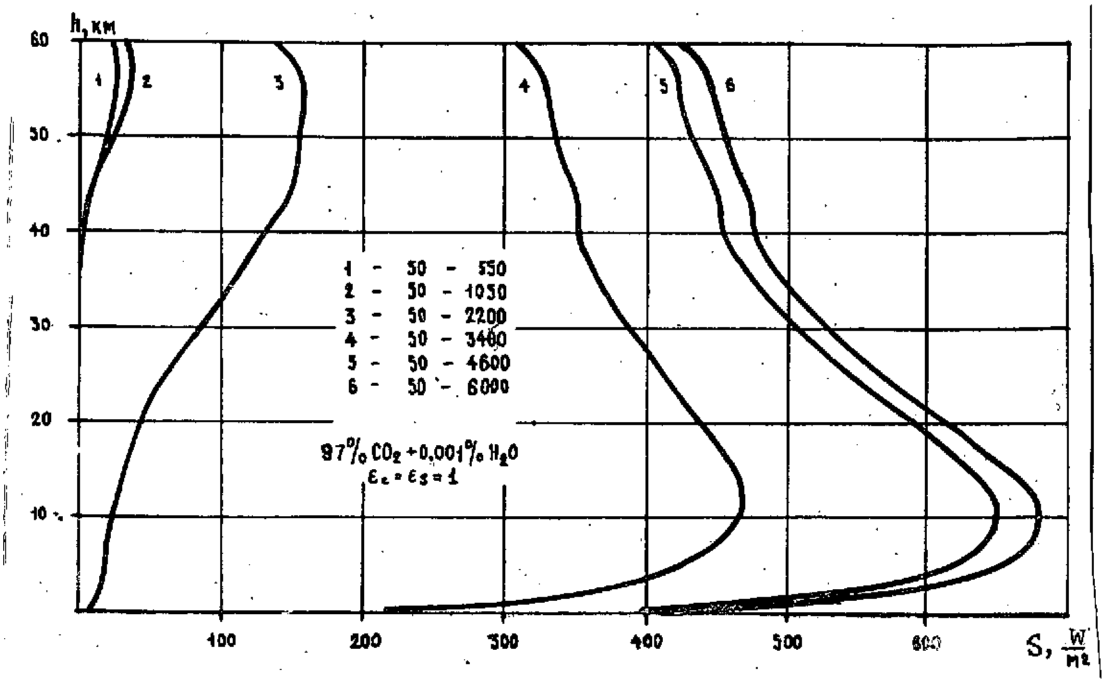

Fig. 15. /39

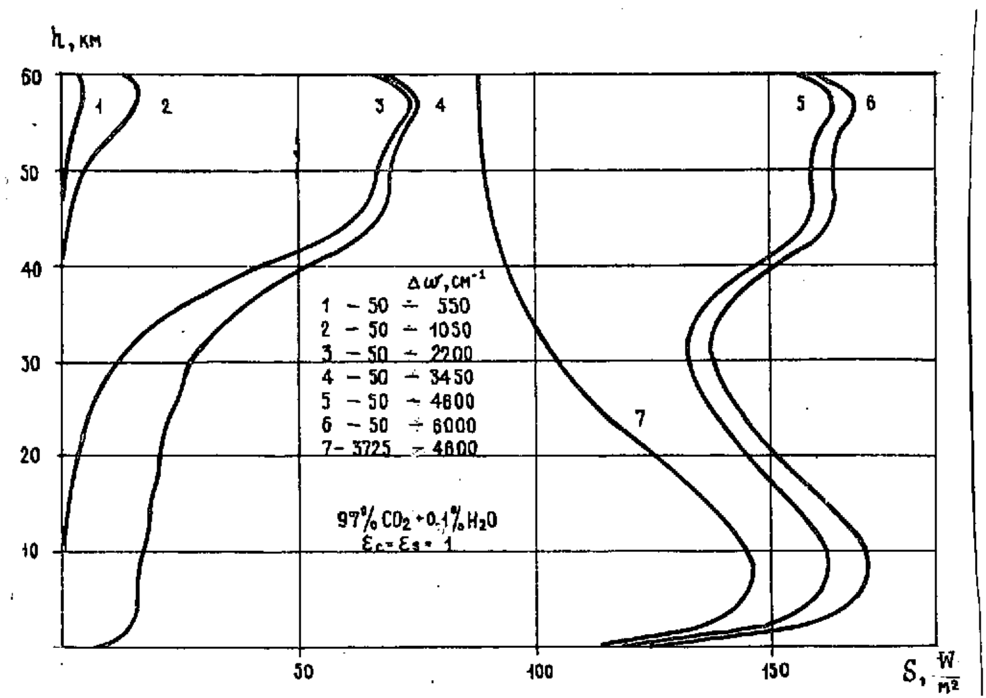

Fig. 16. /40

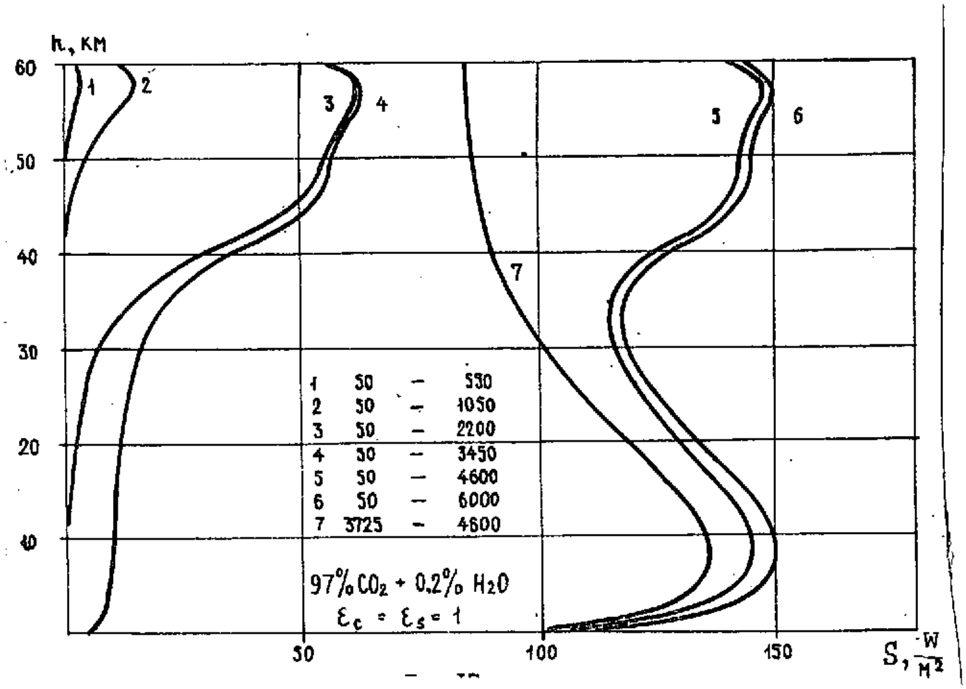

Fig. 17. /41

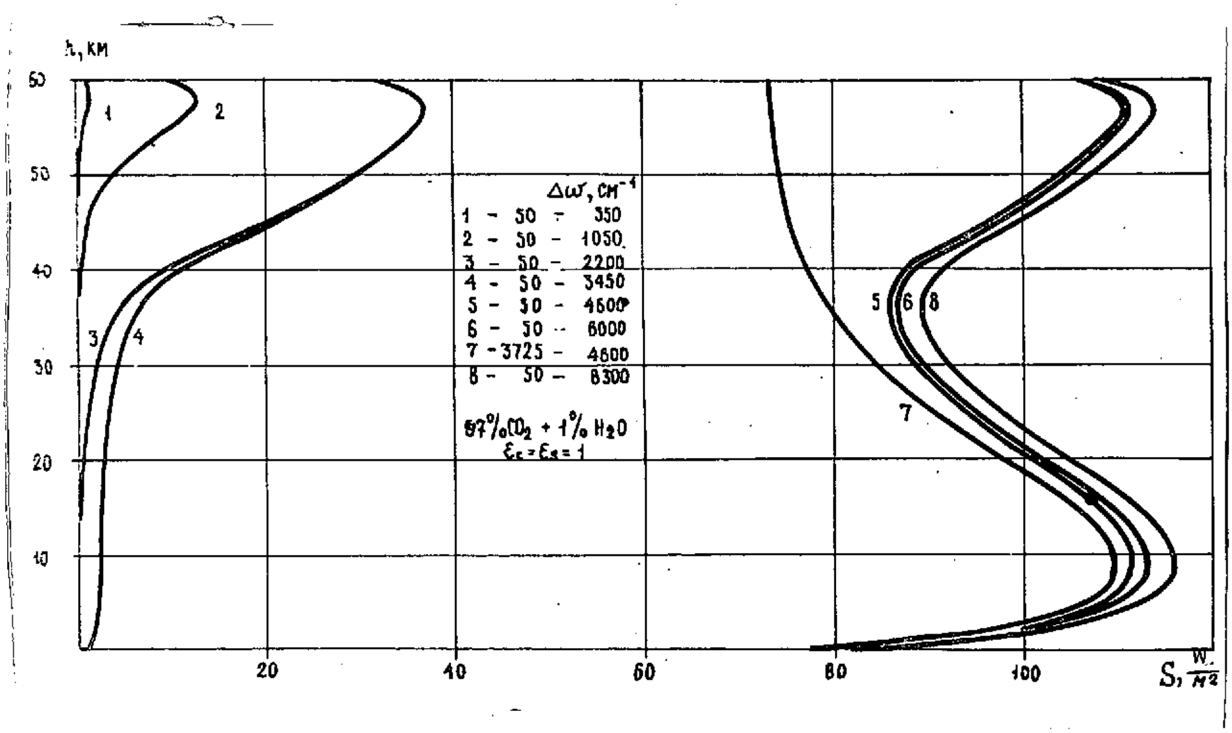

Fig. 18. /42

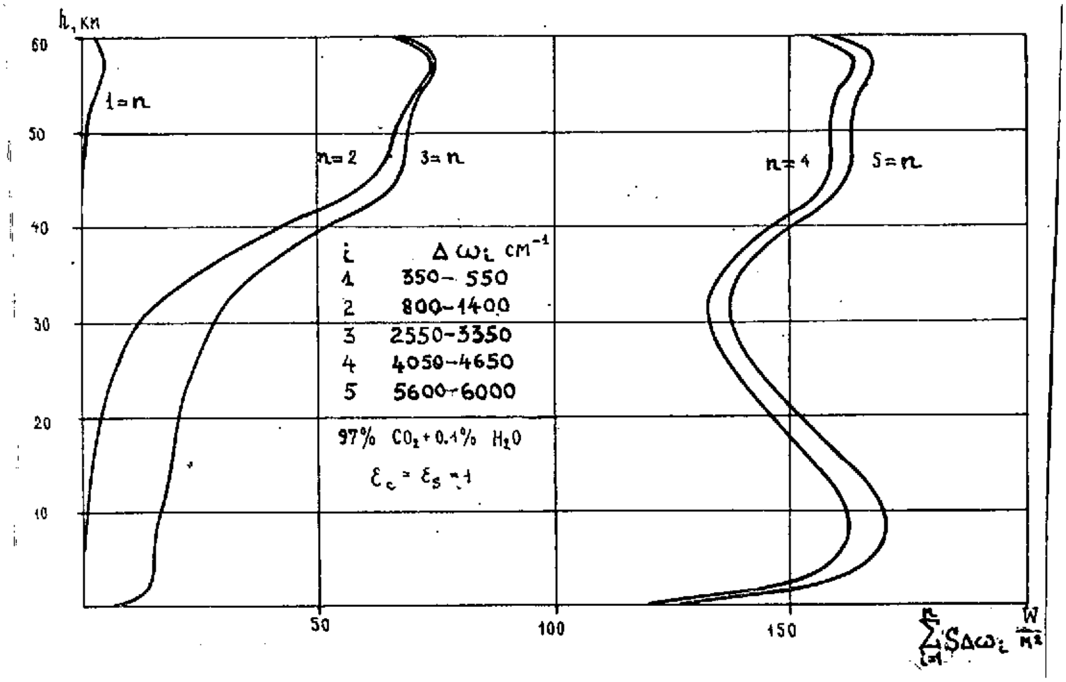

Fig. 19. /43

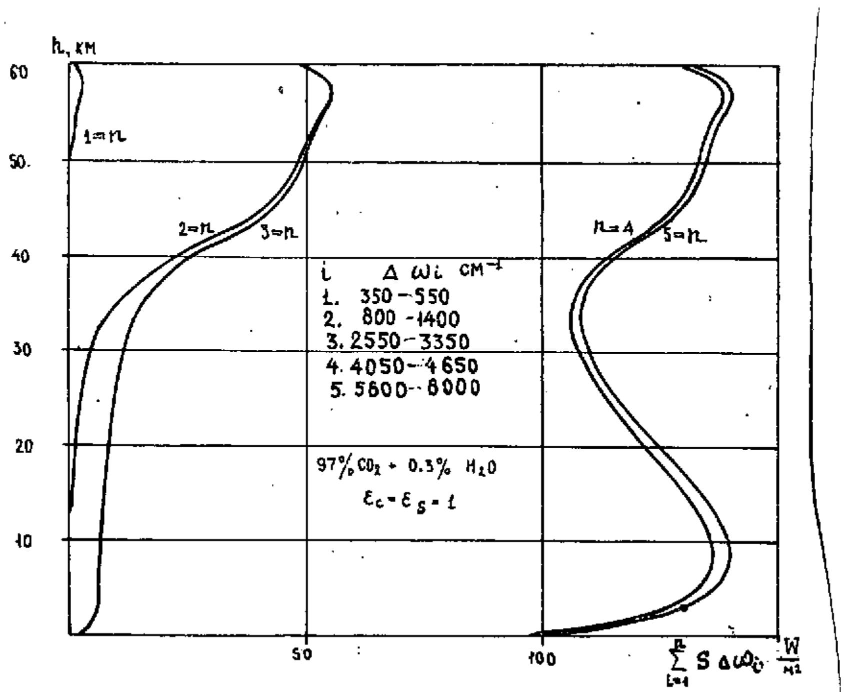

Fig. 20. /44

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